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Developing the Federal Aviation Administration's Requirements for Color Use in Air Traffic Control Displays

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16. Abstract

This report describes the materials we developed for the Federal Aviation Administration's requirements for color use in Air Traffic Control (ATC) displays. While many color use guidelines and the Federal Aviation Administration's Human Factors Design Standard (HF-STD-001) provide general information about how to choose color schemes in visual displays, the purpose of this document is for developers of ATC technologies and human factors practitioners to evaluate the use of color from the perspective of ATC operations. This document provides two checklists. The first is a "To-do" checklist to assess whether the use of a color is effective for its intended purpose of assisting ATC task performance. The second is a "Do-not do" checklist to assess whether the use of color introduces potential negative effects on performance. While the two checklists may not cover all color use issues, they are pertinent to performance and can serve as a baseline to qualify/disqualify color schemes in ATC displays. Developers and human factors practitioners are encouraged to reference these checklists for interface design and acquisition evaluation of ATC technologies.

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DEVELOPING THE FEDERAL AVIATION ADMINISTRATION'S REQUIREMENTS FOR COLOR USE IN AIR TRAFFIC CONTROL DISPLAYS

I. INTRODUCTION

During the past decade, new technologies and automation tools in the air traffic control (ATC) environment have led to the increasing use of color displays. However, the Federal Aviation Administration (FAA) has not established any formal requirements for the use of color in displays or systematic methods to evaluate the benefits or disadvantages of color use. While many existing guidelines for the use of color provide some principles of how to apply colors in visual displays, most of them are largely concerned with color perception rather than the effects of color on task performance in a complex, dynamic environment like ATC.

The intent of this report is to provide a systematic method to assess the benefits and potential disadvantages of color use from an ATC operational perspective. The method helps to ensure that the use of color in ATC displays enhances task performance and does not introduce undesirable safety risks. In 2004, site visits were conducted at nine ATC facilities (three Air Traffic Control Towers, three Terminal Radar Approach Control facilities, and three En Route Traffic Control Centers). At each of the nine facilities, two researchers 1) observed how controllers used color information to perform tasks, 2) identified color uses and their relevance to ATC tasks, and 3) determined potential problems and factors associated with color use. In addition, the advantages and disadvantages of using colors in their displays were discussed with facility representatives (controllers, supervisors, training managers, and quality assurance specialists). The discussions significantly contributed to the task of identifying color and visual factors that might aid or negatively affect ATC task performance (Xing & Schroeder, 2006a).

Through the site observations, a good understanding was gained of how controllers use colors for their work. Colors were found to be used primarily for three purposes associated with ATC task performance: 1) to draw attention to urgent information, 2) to identify data categories, and 3) to segment complex scenes. Many color and visual factors pertinent to controllers' task performance were also identified and then classified into two major categories: 1) factors that make the use of a color beneficial for a given purpose, and 2) factors that have the potential to negatively affect task performance. Based on these results and findings from cognitive and visual research, two checklists were developed to evaluate color schemes in ATC displays. The first checklist evaluates the effectiveness of a color in achieving the intended purpose; the second checklist evaluates the potential disadvantages of color use.

This report is based on information derived from ATC operations and is intended as a general resource for both developers of ATC technologies and human factors practitioners in the evaluation of color use. The FAA's standard practices document, BASELINE REQUIREMENTS FOR COLOR USE IN AIR TRAFFIC CONTROL DISPLAYS, is currently being developed from the materials presented in this report. When completed, the standard practices document will serve as the official guide for vendors of ATC technologies.

Although we used the literature from the visual and color research domains to provide a rationale for the checklists, this report is not intended to serve as an introduction to color science. More information about how color works and how to use color in general visual displays can be found in many color use guidelines (Reynolds, 1994; Cardosi & Hannon, 1999; Ahlstrom & Longo, 2003; Narborough-Hall, 1985; Van Laar, 2001, NASA Color Usage Webpage, 2004).

II. HOW TO USE THIS REPORT

Throughout this report, "**shall**" and "**should**" statements that are common in design specifications will be used. A "**shall**" statement refers to a described, testable condition that must be met. A "**should**" statement refers to a condition that is not completely testable but is recommended. Most "**shall**" and "**should**" statements in this report are accompanied by a paragraph of explanation that provides additional information about the statement and the related scientific literature.

The main body of this report is presented in the following three sections. Section III requires that the use of a color in an ATC display **shall** be associated with a purpose that assists ATC task performance, and the section describes the primary purposes of *attention*, *identification*, and *segmentation*. Section IV requires that the use of a color **shall** be effective for its given purposes and describes the conditions under which the use of color is effective. Section V requires that the use of a color **shall** not introduce potential disadvantages to ATC performance and describes the conditions under which the use of color can limit performance and then

pose safety risks. To meet the color use requirements for ATC displays, all colors used in a display **shall** comply with the statements specified in each of the three sections. In addition, short versions of Sections IV and V are provided in the formats of a "To-Do" and a "Do-Not Do" checklist in Appendices A and B.

III. HOW TO USE COLOR IN ATC DISPLAYS

Color **shall** be used only when it is associated with a purpose that aids task performance. The use of color in ATC displays is typically associated with one of the following three purposes: *attention, identification,* or *segmentation*.

Attention – A salient color is used to immediately direct users' attention to alert or emergent information. In this application, a color generally means "urgent, critical, immediate attention is needed." The effective use of color means that the colored target can automatically capture a user's attention or "pop-out" from a complex display (*Pop-out* means that a visual target can be effortlessly detected irrespective of the amount of local visual materials).

Controllers need to instantly detect the onset of critical information in ATC displays, so a target that represents critical information needs to immediately become obvious so as to capture attention. This phenomenon is called "pop-out' in vision research. Pop-out of colored targets in complex scenes is extremely efficient and desirable (Treisman & Gelade, 1980). Pop-out is especially useful when targets need to be detected in large displays, because targets located in the peripheral visual field can be quickly brought to the fovea for detailed inspection.

Identification – A set of colors is used to identify data categories when data are presented dynamically, intermingled, or distributed in an irregular way on a display. In this application, each color is associated with a specific meaning. The effective use of color for identification means that searching by color for an item of a given category among many other items can be done effortlessly, accurately, and reliably.

While our sensory system can perceive a large amount of information, our cognitive system can only process a few pieces of information at a time. Therefore, an efficient way to handle a large amount of data is to classify data into categories and denote the categories with visual attributes that can be easily identified. Such tasks are called *identification*. Color is often the most effective search attribute for difficult visual identification tasks; searching for data of a given category by color can be effortless, accurate, and reliable (Christ, 1975). *Effortless* often implies *quick*, as when the time required to find an item does not depend on the total number of items displayed. *Reliable* means that selection is consistent and dependable. *Accurate* means that, statistically, the correct item is always selected and the incorrect item is not selected. The superiority of color to achromatic cues is more evident as the visual scenes become more complex or the difficulty of identification tasks increases (Sachtler & Zaidi, 1992).

Segmentation – Different colors are used to organize information by segmenting a complex scene into distinctive visual objects. In this application, a color is not necessarily associated with a meaning. It is merely used to integrate or differentiate data. The effective use of color for segmentation means that data displayed in the same color appear as a visual object separated from other data so that a user will know where to look for related information. Such visual objects can be either spatially continuous regions (such as an image) or spatially discontinuous patterns (such as a figure).

The human visual system organizes a complex scene into meaningful objects. To appreciate what and where particular information is present, the visual inputs are organized by a filtering procedure that has been termed *segmentation* (Julesz, 1965; Pinker, 1984). Segmentation means that some visual inputs are integrated as one object by a common visual attribute, and that object is represented differently from other objects. Segmentation tasks include regional segmentation and pattern segmentation. Regional segmentation involves segmenting a spatially continuous region from its surrounding materials; pattern segmentation involves integrating some spatially discontinuous items into one object and segmenting them from other displayed items. Segmentation is crucial when using an automation system with a cluttered display and varying task demands. In complex displays like those used in ATC, color is more effective and is processed faster than achromatic cues for segmentation (Treisman & Gelade 1980; Nothdurft, 1993).

Other than the three primary task-related purposes of *attention*, *identification*, and *segmentation*, color is occasionally used to label data. This application is typically used in the situation where many categories of data are displayed irregularly and intermingled across a display, yet the available space is insufficient to label the data with text. Therefore, colors are used to label the data and a look-up table is provided to indicate the meaning of each color. The use of color for this purpose appears similar to that for *identification*. However, the colors in this application are only for labeling, not for controllers to efficiently and reliably search the data included in a given category. Thus, as long as the colors are visually distinguishable and a look-up table is provided, they can adequately serve the purpose. Because the application of color for data labeling is rare and easy to use, this kind of color use is not included in Section IV, "How to effectively use color to aid task performance."

IV. HOW TO USE COLOR EFFECTIVELY TO AID TASK PERFORMANCE – A "TO-DO" CHECKLIST

A color can be mathematically specified by its luminance and chromaticity parameters (see Appendix C for details). Visual research has demonstrated that the effectiveness of color for a given task depends on luminance, chromaticity, the number of colors used, and other factors. This checklist was developed by integrating visual research results with ATC color application requirements.

The checklist is organized with respect to the three primary task purposes of color use in ATC displays. For each purpose, *shall* and *should* statements are used to describe the conditions required for the color use to be effective. To utilize this checklist, first determine the purpose of a color usage and then evaluate the conditions for that purpose. Only when all the conditions for a given purpose are met can the use of color be effective. If a color is used for more than one purpose, then all the conditions under those purposes need to be met for the color being effective. A short version of this checklist is presented in Appendix A.

Task Purpose: *Attention*

The following conditions **shall** be met for a color to be effective in capturing attention.

> *1) Luminance*: The apparent luminance of the target that requires attention shall be no less than the luminance of other displayed data (called *distracters*) in the view field.

The luminance of the target that requires attention **should** be high enough so that the target remains salient even when controllers reduce the screen brightness.

The pop-out effect depends on the salience of a visual target relative to the distracters. Brightness (i.e., luminance) contributes to salience more than color; thus, a brighter target among dimmer distracters can easily pop-out while a dimmer target among brighter distracters fails to pop-out, regardless of its chromaticity (Li, 1999; Treisman & Souther, 1985). In addition, high luminance is desirable for mission-critical targets in an ATC work environment because the targets need to be visible and salient even when controllers reduce the brightness of their computer screens.

The apparent luminance is the luminance of a visual object perceived by the eyes. It can be estimated as the area of the object multiplying the physical luminance. For instance, the apparent luminance of a text box filled with a color is about 5 times higher than the apparent luminance of the text of the same color because text only takes about 20% of the area.

> 2) *Luminance difference* or *chromaticity difference*: The apparent luminance of the target shall be at least 20 cd/m^2 greater than that of distracters. Alternatively, the absolute chromaticity difference between the target and distracters shall be greater than 0.24 in International Committee of Illumination (CIE) uniform chromaticity coordinates (see Appendix C for details).

Either the luminance difference between a target and distracters or the chromaticity difference between them can make the target pop-out from distracters. Nagy and Sanchez (1992) found that the minimal luminance difference for a target to capture attention was about 20 cd/m^2 for small targets (0.5~1.5 degree view angle) presented in large displays. Alternatively, the chromaticity difference between the target and distracters has to be greater than 40~60 times the color discrimination threshold. Notice that the chromaticity difference can produce pop-out only when the luminance of the target is no less than that of the distracters.

> 3) *Number of distracter colors*: The number of distracter colors shall be fewer than five.

For the best effect, the number of distracter colors **should** be minimized to no more than two or three.

Color is effective in inducing pop-out when other materials of comparable or larger sizes in the view field are composed of no more than two or three colors. With increasing variation of distracters, target salience decreases and the pop-out effect diminishes (Treisman & Gelade, 1980).

Task Purpose: *Identification*

The following conditions **shall** be met for a set of colors to be effective in identifying data categories.

> *1) Color naming*: The colors used to identify data categories shall be reliably and consistently named.

Basic colors **should** be chosen for the purpose of *identification*.

In the ATC environment, identification of data categories is usually performed at different spatial locations and times. Therefore, the task of using color for identification is essentially the task of color naming in which controllers

associate the data with specific color names and search for the color of the given name from memory. Color research has found that 11 basic colors can be reliably and consistently named across populations of different geographic regions and different cultures. Those are red, green, yellow, blue, pink, brown, purple, orange, and three achromatic terms, black, white, and gray (Boynton & Olson, 1990). These colors are maximally separated in the color space. In addition, magenta and cyan are also among the consistently namable colors. Visual experiments have demonstrated that basic colors work better than non-basic colors when identifying data categories in complex scenes and for complicated tasks (Smallman & Boynton, 1990; Guest & Van Laar, 2002).

2) Chromaticity difference: **If non-basic colors are used for *identification*, the chromaticity differences between the colors shall be greater than 0.04 in CIE uniform coordinates.**

The chromaticity difference between the colors **should** be significant enough for each color to be distinctively named.

The minimal chromaticity difference for colors to be distinctively named is about 10 times the color discrimination threshold (Boynton, MacLaury, & Uchikawa, 1989; Poirson & Wandell, 1990). If the chromaticity of two colors is too close, the similarity in the two colors interferes, making it difficult to use the color name as the criterion to search the data in a category.

3) Number of colors: **The number of colors used to identify data categories shall be fewer than seven.**

Visual experiments have demonstrated that color has no advantage over achromatic cues for *identification* when the number of colors used is greater than 6~7 (Carter, 1982). Furthermore, using more than six colors for identification can result in an increase in errors of omission when users perform multiple tasks (Cummings, Tsonis, & Xing, 2007).

4) Luminance difference: **The luminance difference between the colors shall be less than 20 cd/m^2.**

The luminance difference between the colors **should** be minimized so that none of the colors is much brighter than the others.

When the luminance difference between two colors is greater than 20 cd/m^2, the data displayed in the brighter color can pop-out to capture users' attention (Nagy & Sanchez, 1992). Therefore, a bright color becomes a distraction when users search for the data displayed in the dimmer color. Consequently, users tend to miss the data included in that category, and the dimmer color becomes ineffective for identification. When the levels of importance of data categories need to be emphasized, it is better to manipulate color hues rather than luminance. For instance, when one of the data categories has a higher priority than other categories and needs to be pointed out to controllers, yellow or red-orange are often assigned to the category because those colors have a hue close to red.

5) Luminance: **The luminance of the colors should be high enough so that the colored data can be reliably detected even when controllers reduce their screen brightness.**

Controllers can adjust the brightness of their displays. As a result, some low-luminance colors may become invisible. It is important for the developers of ATC technologies to be prepared for such circumstances. At present, the FAA has no requirement for the lower-limit of controllers' brightness adjustments (Ahlstrom & Arend, 2005).

Task Purpose: *Segmentation*

The following conditions **shall** be met for a color to be effective in segmentation.

1) Luminance ratio **or** *chromaticity difference*: **For regional object segmentation, the chromaticity difference between the object and its surrounds shall be greater than 0.004. Alternatively, the luminance ratio, defined as the absolute luminance difference between the object and surrounds divided by the luminance of the object, shall be greater than 5%. For pattern segmentation, the color difference between the pattern and its surrounds shall be greater than 0.012. Alternatively, the luminance ratio shall be greater than 15~20%.**

Both chromaticity and luminance differences between two visual regions or patterns can result in segmentation; however, chromaticity is more effective than luminance. Theoretically, segmentation can be achieved when the chromaticity difference is greater than the color discrimination threshold, which is estimated as 0.004 in CIE uniform chromaticity coordinates and at which two filled areas placed side-by-side can be reliably discriminated (Wyszecki & Fielder, 1971). However, it takes about three times the discrimination threshold for two spatially discontinuous patterns to be reliably segmented.

The effect of luminance in segmentation is determined by the ratio of the luminance difference to the baseline luminance of the object to be segmented. The threshold ratio is about 5% for regional segmentation and 15~20% for pattern segmentations (McIlhagga, Hine, Cole, & Snyder, 1990).

2) Luminance difference: When the color difference is sufficient for segmentation, the luminance difference shall remain the same for data that are of equal importance.

The luminance difference between data of equal importance **should** be minimized so they appear to have the same visual salience.

Because the salience of a visual object increases with its luminance, having the luminance levels of the displayed data consistent with the levels of data importance can help to organize data priorities. On the other hand, less important data (such as background information) may be integrated and segmented by less brighter colors.

3) Number of colors: The object to be segmented shall consist of no more than two colors unless the object is composed of high-density textures of various colors.

A region consisting of two or more colors is likely to be confused with other regions made up of many colors (Julesz, 1965); thus, it may not be reliably segmented from others.

V. HOW TO AVOID POTENTIAL DISADVANTAGES OF COLOR USE – A "DO-NOT DO" CHECKLIST

The visual and cognitive factors underlying the negative instances of color use in ATC displays were analyzed and classified. Eight factors, with which the use of color has potential disadvantages for task performance, were identified. Those are*: low text readability, lack of an effective redundant cue, color complexity, excessive coding sets, experience interference, uncorrelated coding, loss of integration,* and *distraction.* The conditions for how to prevent the factors from occurring in ATC displays were identified by integrating the findings in the literature with ATC color applications. These conditions are included in this "Do-not do" checklist of color use. A *shall* or *should* statement is used to describe the condition for each factor. The potential consequences of the presence of a factor are also described. To avoid safety risks, the use of a color in an ATC display **shall** be checked for the presence of each factor and meet all the statements provided. See Appendix B for a short version of the "Do-not do" checklist.

1) *Low text readability*: The luminance contrast between the text and background shall be greater than the threshold contrast (30%) for error-free reading.

Potential consequence: Low text readability increases reading difficulty and may cause reading errors.

Readability is the property that permits a user to easily read text on a screen irrespective of meaning (Legge, Rubin, & Luebker, 1987). It is primarily determined by the luminance contrast between the text and its background colors. Luminance contrast can be calculated as the difference between the text and background luminance divided by the sum of the luminance. Therefore, zero contrast means that the text and background have the same luminance, and 100% contrast describes the maximum luminance contrast such as the contrast produced by the combination of white and black. The text readability is trimmed to zero when both the text and background luminance is very low (typically less than 10 cd/m^2 for many computer monitors), regardless of the luminance contrast (Krebs, Xing, & Ahumada, 2002). Several experimental studies have demonstrated that readability decreases linearly with luminance contrast. In particular, readability deteriorates significantly below 20~30% contrast (Legge et al., 1987; Scharff & Ahumada, 2002). Furthermore, Krebs et al. (2002) found that for a given monitor the minimum text size for error-free reading varied with text contrast when the contrast was less than 20%; while the minimum size was a constant within the contrast range of 20-100%. Based on these and many other studies, the threshold contrast for error-free reading is set at 30%. Appendix D describes how to calculate the text contrast from the color specifications of a text and its background.

2) *Lack of effective redundant cue*: The use of color for attention or identification shall be accompanied with effective redundant cues.

Potential consequence: Lack of effective redundant cues means that color is the only cue to draw attention or identify data categories. Lack of effective redundant cues may result in loss of color-coded information when colors are viewed by color-vision-deficient users, from off-axis angles for flat panel displays, or under strong ambient light.

About 8~10% of all males have various types of color vision deficiencies, yet the FAA's current color vision

Table 1. Effectiveness of Redundant Cues Relative to Color for Various Tasks

Task	Flashing	Location	Luminance	Shape	Size	Text
Attention	E[a]	L[b]	E	NE[c]	NE	NE
Identification	NA[d]	E	NE	L	NE	L
Segmentation	NA	L	L	L	L	NE

[a]E = redundant cue is more effective than or at least as effective as color
[b]L = cue is less effective compared to color
[c]NE = cue is not effective for the task
[d]NA = cue is not applicable

standard for air traffic control applicants allows individuals with some degree of color vision deficiencies to enter the workforce (based on a demonstrated ability to pass a job-related practical test; Mertens, Milburn, & Collins, 2000). In addition, displayed colors tend to be distorted or washed out when viewed from off-axis angles for flat panel displays or under strong ambient light. Therefore, when a color is used for *attention* or *identification*, achromatic cues **should** be available, in addition to color, to encode the information as a redundancy. It is important that redundant cues are effective for the given purpose.

Table 1 lists the effectiveness of some frequently used redundant cues for different task purposes, where "E" means that the redundant cue is as effective as color, "L" means that the cue is less effective compared to color, "NE" means that the cue is not effective for the task, and "NA" means that the cue is not applicable for the task. For *attention*, typical effective cues include flashing / blinking and luminance; effective cues for *identification* include spatial location, distinctive shape, and text (Xing & Schroeder, 2006b).

3) Color complexity: The number of colors used to identify data categories in a single display mode shall be fewer than seven.

Potential consequence: Using colors for *identification* places additional demands on working memory. Moreover, exceeding the working memory capacity (about seven items) can cause users to make more omission errors when performing multiple tasks.

Using colors to identify data categories can reduce the time needed to search for the data and increase performance accuracy. However, to take the advantages of color, color names must be related to their assigned meanings, which burdens the working memory. Since the number of items that can be maintained in working memory is limited (about 7 ± 2, Miller, 1965), it is not surprising that color has no advantages over achromatic visual cues when more than six color categories are used (Carter, 1982). Furthermore, in situations where color is used to identify data categories while users also perform other tasks such as planning or monitoring, using more than six colors results in an increase of omission errors in the other tasks (Cummings et al., 2007).

4) Excessive coding sets: A display shall use no more than three sets of colors to identify data categories.

Potential consequence: Multiple sets of color-coding can increase cognitive workload and cause misinterpretation of information.

An ATC display typically contains multiple data groups. For example, a radar display may have datablocks as one data group and weather information as another group. Each data group can contain several categories of data. While identifying the categories of one or two data groups by color may help to search the data of a given category, there is no clear advantage of using color when multiple sets of color-coding are used (Yuditsky, Sollenberger, Della Rocco, Friedman-Berg, & Manning, 2002) because remembering the color meanings and switching between the sets increase cognitive workload; and because users tend to mistake the meanings of the colors in the less-frequently-used color sets. In addition, using multiple coding sets is often accompanied with another negative color factor, uncorrelated coding: one color for multiple meanings.

5) Experience interference: The use of a color shall not conflict with its reserved meanings, according to the color use conventions in ATC displays.

Potential consequence: Interference occurs when the meaning of a color conflicts with controllers' previous experiences and may result in misinterpreting information and increasing the cognitive workload required to comprehend color meanings.

There are some conventions about color use in ATC displays, and controllers have acquired reserved color meanings associated with those conventions through experience. If a color use conflicts with its reserved meaning, what is in the experience and the perceived information may interfere with each other, and the perceived information can be biased by experience (Stroop, 1935). The following is a list of conventions for color usage in ATC displays:

- Red is reserved to draw attention to emergency or alert messages.
- Yellow is reserved to identify a target or data category that needs caution.
- Orange, purple (or magenta), and cyan (or turquoise) are typically used to identify data categories; green, white, and black are often used to identify the category of the normal status.
- Non-basic colors, especially those in the green-blue domain (e.g., green-blue, gray-blue, and yellowish-green) are the typical choices for segmentation.

6) Uncorrelated coding: When used for *attention* or *identification*, a color shall be fully correlated with a specific meaning in task performance; and information of the same category shall be represented by the same color.

Potential consequence: Uncorrelated color-coding causes coding uncertainty, which may decrease the accuracy of identifying data in a category and cause misinterpretation of color-coded information.

Color has significant advantages in identification tasks only when it is fully correlated with the information it denotes. If a color is only partially correlated with the content of information, then a user cannot use the color as the unique selection criterion for decision-making; therefore, the color has no advantage over achromatic attributes (Christ, 1975). Moreover, such color-coding may cause performance errors because it introduces uncertainty to the signal processing. By the theory of signal detection, increasing uncertainty of the selection criterion leads to a higher probability of decision errors.

7) Loss of integration: Data that need to be momentarily related for successful task performance should be displayed in the same or similar colors.

Potential consequence: Displaying two sets of data in different colors reduces instant information integration between the data sets because a user is less likely to recognize the relationships between pieces of information when they are depicted in different colors.

The brain processes color information with two mechanisms: integrating pieces of information depicted in the same color and segregating information depicted in different colors. Segregation and integration are like the opposite ends along an axis in that a higher level of segregation is always accompanied with a lower level of integration, and vice versa. The brain processes different colors separately, and it has to intentionally make an extra effort to integrate information represented by different colors. Thus, the brain is less likely to automatically associate pieces of information displayed in different colors compared to those displayed in the same color, especially when the data are displayed dynamically. This lack of association poses a risk in tasks where data in different categories need to be simultaneously related.

8) *Distraction*: Multiple salient colors that need attention shall not be onset simultaneously in a single display mode.

Potential consequence: The onset of a salient target causes distraction, which may decrease the detection of other significant events and result in loss of information even if the events are visually salient and are in the focus of view.

Attention to a target implies withdrawal from other data to effectively deal with the target. Since the ability to attend to visual inputs is limited, attending to a salient target in a complex scene acts as a distraction for other inputs in the scene. Therefore, the perception of other inputs is reduced. Hence, what facilitates attention is also the source of distraction. In extreme circumstances, the pop-out of a salient target can induce a phenomenon known as "inattentional blindness," which means when focusing attention on a salient object, one often fails to notice other salient objects or events occurring simultaneously (Simons, 2000; DiVita, Obermayer, Nugent, & Linville, 2004). Visual experiments have demonstrated that salient targets capture attention and enter into the awareness one at a time; other targets may be ignored (Schmidt, Vogel, Woodman, & Luck, 2002). Therefore, the use of color for the purpose of *attention* **should** be limited and applied with caution.

VI. CONCLUSIONS

This report presents the materials for the development of the FAA's requirements for color use in ATC displays. The report describes two checklists. A "To-do" checklist assesses whether the use of a color is effective for its intended purpose so that it aids ATC task performance; a "Do-not do" checklist assesses whether the use of color introduces potential negative effects on ATC performance. These two checklists were based on the observation and analysis of color use in current ATC displays to ensure that they are task-oriented and are specifically applicable to ATC. One advantage of the checklists is their easy-to-use format. A human factors practitioner can quickly go through the checklists for each color in a display and qualify or disqualify the color use. Finally, recall that the materials in this report were intended to serve as a reference to ensure the proper use of color in future ATC technologies. Therefore, this report does not provide detailed information about how to choose a color palette for a display and how to optimize the effects of color. Such information can be found in other color use guidelines ((Reynolds, 1994; Cardosi & Hannon, 1999; HF-STD-001, 2003; Narborough-Hall, 1985; Van Laar, 2001, NASA Color Usage Webpage, 2004).

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APPENDIX A
“To-Do” Checklist for Ensuring the Effectiveness of Color Use

The checklist is organized with respect to task purposes. The elements in Table A-1, from left to right, are task purpose, color and visual factors contributing to the effectiveness of color use, conditions with which color use is effective for the intended purpose, and checkboxes that would be filled with “Yes” if a condition is met or “No” otherwise. To use this checklist, first determine the task purpose of a color. For each purpose, several factors contribute to the effectiveness of color use. When all the conditions for a given purpose are met, the use of color is effective for that purpose.

Table A-1. A “To-do” checklist for ensuring the effectiveness of color use

Task purpose	Visual factors	Conditions for color-use being effective	Yes / No
Attention	Luminance	The luminance of the color-coded target **shall** be equal to or greater than that of distracters (i.e., other materials displayed in the visual field).	
	Luminance or chromaticity difference	The luminance difference between the color-coded target and distracters **shall** be greater than 20 cd/m^2. Alternatively, the chromaticity difference between the color-coded target and distracters **shall** be greater than 0.24 in CIE uniform chromaticity coordinates.	
	Number of distracter colors	The number of distracter colors **shall** be fewer than five.	
Identification	Color naming	The colors used for identification **shall** be reliably and consistently named.	
	Chromaticity difference	The chromaticity differences between non-basic colors **shall** be greater than 0.04 in CIE uniform coordinates.	
	Number of colors	The number of colors used to identify data categories **shall** be fewer than seven.	
	Luminance difference	The luminance differences between colors **shall** be less than 20 cd/cm^2.	
	Luminance	The luminance of colors **should** be high enough to be reliably detected when screen brightness is reduced.	
Segmentation	Luminance ratio or chromaticity difference	For regional object segmentation, the chromaticity difference between the object and its surrounds **shall** be greater than 0.004. Alternatively, the luminance ratio (defined as the absolute luminance difference between the object and surrounds divided by the luminance of the object), **shall** be greater than ~5%. For pattern segmentation, the color difference between the pattern and its surrounds **shall** be greater than 0.012. Alternatively, the luminance ratio **shall** be greater than 15~20%.	
	Luminance difference	When the color difference is sufficient for segmentation, the luminance difference **shall** be kept roughly the same for data that are of equal-importance.	
	Number of object colors	The number of colors of the object to be segmented **shall** be no more than two unless the object is composed of high-density textures of different colors.	

APPENDIX B

“Do-Not Do” Checklist for Avoiding Potential Disadvantages of Color Use

The first column lists the negative factors or potential disadvantages associated with the use of color in ATC displays. The second column lists some potential consequences of the presence of each negative factor. The third column lists the conditions to prevent the negative factors from occurring. The last column consists of checkboxes that can be filled with “Yes” if the condition is met and “No” otherwise. A “No” indicates that the use of color has potential negative effects on task performance.

Table B-1. A “Do-No Do” checklist for avoiding potential disadvantages of color use

Negative factors	Potential disadvantages	Conditions to avoid the disadvantages	Yes /No
Low text readability	Reducing reading speed; increasing reading errors.	The luminance contrast between the text and background **shall** be greater than the threshold contrast (20~30%) for error-free reading.	
Lack of effective redundant cue	Increasing chances of losing or misinterpreting information.	The use of color for *attention* or *identification* **shall** be accompanied with effective redundant cues.	
Color complexity	Increasing cognitive workload; reducing speed of information interpretation; increasing chances of misinterpreting information.	The colors used to identify data categories in a single display mode **shall** be fewer than seven.	
Excessive coding sets	Increasing chances of missing information; users tend to ignore color-coding.	A display **shall** use no more than three sets of colors to identify data categories.	
Experience interference	Increasing cognitive workload; increasing chances of misinterpreting information.	The use of color **shall not** conflict with the reserved meanings of color use conventions in ATC displays.	
Uncorrelated coding	Slower and less accurate in identification compared to using text or symbols alone.	Data identified by a color **shall** be completely correlated with a specific meaning in task performance. In particular, one color **shall not** be used for multiple purposes, and multiple colors **shall not** be used to represent the same information.	
Loss of integration	Less likely to associate pieces of information that are color segmented.	Dynamic data that need to be simultaneously bonded for successful task performance **should** be displayed in the same or similar colors.	
Distraction	Decreased detection of other significant events; loss of information	Multiple salient colors that need attention **shall not** be onset simultaneously in a single display mode.	

APPENDIX C
Measuring/Computing the CIE (International Committee of Illumination) Chromaticity Coordinates of a Color

A computer monitor generates a color through three phosphor channels: red, green, and blue. The amount of phosphors emitted from a channel is specified with 8-bit digital values of the channels: *r, g*, and *b*, each for red, green, and blue phosphors. Computer programmers use these three numbers to specify a color on displays. For example, *rgb* values of 255, 0, 0 represent red, and 255, 255, 0 are yellow. While *rgb* values specify the physical attributes of a color on a monitor, they do not tell how viewers perceive the color.

The International Committee of Illumination (CIE) defined color chromaticity coordinates to describe human color perception (CIE, 1931). In this definition, a color can be specified by three variables: *L, x,* and *y,* where *L* is the luminance of a color while *x* and *y* determine the hue; *x* and *y* vary between 0 and 1. For example, the typical values for white in a computer monitor are *x*=0.3300 and y=0.3515; the values for red are x=0.6340 and y=0.3337. The *xyL* values of a color surface can be measured with a colorimeter.

The relationship between *rgb* and *xyL* values can be specified with a nonlinear transformation and a linear matrix transformation, as described by the following equations:

$R=(r/255)^{gamma}$

$G=(g/255)^{gamma}$

$B=(b/255)^{gamma}$

Where the parameter *gamma* describes the nonlinearity of luminance response for a given monitor. It usually varies in a range of 1.8-2.5 for CRT monitors, with a typical default value of 2.2. The transformation between RGB values and CIE chromaticity coordinates (*xyL*) are determined by the following equations:

X=40.9568*R + 35.5041*G + 17.9167*B;

Y=21.3389*R + 70.6743*G + 7.98680*B;

Z=1.86297*R + 11.4620*G + 91.2367*B;

And,

x=X/(X+Y+Z)

y=Y/(X+Y+Z)

L=Y

Notice that the parameters in these transformations vary from monitor to monitor. The numbers in the equations above are typical default values for CRT displays. The process of determining the parameters of the transformations for a given monitor is called *color calibration.*

One of the greatest disadvantages of the CIE chromaticity systems is that visually the coordinates are not equally spaced. Thus, distortions occur in attempting to relate perceived colors to locations of the CIE chromaticity diagram. Based on the *xyL* systems, the CIE adopted the *Lu′v′* uniform chromaticity coordinates that were more nearly uniformly spaced with respect to color perception (CIE, 1986). Therefore, the chromaticity difference between two colors can be computed as $((\Delta u')^2 + (\Delta v')^2)^{1/2}$. The values of *u′* and *v′* can be computed from *x* and *y* through two non-linear equations:

u′ = 4x / (-2x+12y+3)

v′ = 9y / (-2x+12y+3)

APPENDIX D
Estimating Text Readability on Visual Displays

Text readability is determined by the luminance contrast of the text and background colors. There are several definitions of luminance contrast. The one that is most commonly associated with text readability is Michelson contrast, defined as $(L_t - L_b) / (L_t + L_b)$, where L_t is the text luminance and L_b is the background luminance. The contrast varies between 0 and 1, or 0 to 100%. The contrast zero means that the background color is the same as the text color; thus, the text is completely invisible. The 100% contrast corresponds to the maximum luminance contrast that can be achieved in an ideal display. The contrast threshold for error-free reading is typically taken as 20~30%. Below we provide step-by-step procedures to measure or estimate text readability.

Step 1: Obtain the text luminance L_t and background luminance L_b

Three procedures are provided to comply with different situations. Users may choose the one that is most suitable to their needs.

Procedure 1A: This procedure works for the situation where users 1) know the *rgb* values of the colors, 2) have a colorimeter or luminance meter to measure luminance, 3) are capable of generating a color patch on the given computer monitor, and 4) intend to get the accurate text readability for a given text.

Step 1A.1: Set up the room lighting similar to that of the work environment;

Step 1A.2: Generate a square patch uniformly filled with the text color (specified by the *rgb* values) on the center of the screen while keeping the rest of the screen black (specified by r=g=b=0).

Step 1A.3: Hold the colorimeter at users' typical view distance and measure the luminance of the patch. That is the L_t.

Step 1B.4: Repeat 1A.2 and 1A.3 with the text background color to obtain L_b.

Procedure 1B: This procedure works for the situation where users 1) know the *rgb* values of the text and background colors, 2) have a colorimeter or luminance meter to measure luminance, 3) have done color calibration of the monitor and so as to obtain the *gamma* value of the monitor, and 4) do not want to spend time measuring luminance values for every individual text / background color.

Step 1B.1: Set up the room light similar to that of the work environment;

Step 1B. 2: Generate a patch uniformly filled with the color (255, 0, 0) on the center of the screen while keeping the rest of the screen black (specified by r=g=b=0).

Step 1B. 3: Hold the colorimeter at users' typical view distance and measure the luminance of the patch. That is the value for L_r.

Step 1B.4: Repeat 1B.2 and 1B.3 with the color (0, 255, 0) to obtain the value L_g;

Step 1B.5: Repeat 1B.2 and 1B.3 with the color (0, 0, 255) to obtain the value L_{blue};

Step 1B.6: Set the full screen at r=g=b=0 and measure the luminance as the value L_0

Step 1B.7: Using L_r, L_g, L_{blue}, L_0, and *gamma* values to compute the luminance for any given text color specified with *rgb* values by the following equation:

$$L_t = L_r * (r/255)^{\text{gamma}} + L_g * (g/255)^{\text{gamma}} + L_{blue} * (b/255)^{\text{gamma}} + L_0$$

The same equation can be used to calculate the background luminance L_b with the *rgb* values of the background color.

Procedure 1C: This procedure works for the situation where users don't have any measurement equipment so they can only estimate the luminance of the colors.

Step 1C.1: Try to find the color parameters (*gamma,* L_r, L_g, L_{blue}, *and* L_0) for the monitor, where L_r, L_g, L_{blue}, *and* L_0 are the screen luminance measured at the *rgb* values: (255, 0, 0), (0, 255, 0), (0, 0, 255), and (0, 0, 0) respectively. *Gamma* is the non-linearity parameter of a monitor. These parameters vary from monitor to monitor.

Step 1C.2: Using L_r, L_g, L_{blue}, L_0 and the *gamma* value to compute the luminance for any given color specified with *rgb* by the following equation:

$$L_t = L_r * (r/255)^{\text{gamma}} + L_g * (g/255)^{\text{gamma}} + L_{blue} * (b/255)^{\text{gamma}} + L_0$$

This equation allows you to calculate the text luminance L_t with the *rgb* values of a text color and the background luminance L_b with the *rgb* values of the background color.

In the worst case where none of the color parameters is available, here are some default values used for typical CRT displays:

L_r = 21.3389, L_g =70.6743, L_b =7.98680, and *gamma*= 2.2, while L_0 may vary from 3 cd/m^2 to 12 cd/m^2 depending on the ambient light.

Step 2: calculate the text contrast

Text contrast (the Michelson contrast) is defined as $(L_t - L_b) / (L_t + L_b)$, where L_t is the text luminance and L_b is the background luminance. The contrast varies between 0 and 100%.

When both background and text colors are very dark, the text readability is determined by the luminance difference between the text and background, rather than the contrast. Therefore, we use the following equations to approximate the text contrast C:

C= $L_t - L_b) / (L_t + L_b)$, if L_t > 10 cd/m^2 or L_t >10 cd/m^2

Else

C=0

Step 3: Compare the text contrast with the threshold error-free-reading contrast (recommended as 30% in this report).

If C >= 30% (or 0.3), the text readability meets the requirement;

If C < 30%, the text readability does not meet the requirement.